



Fermilab Site Filler Collider Options

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Special thanks to Tanaji Sen, David Neuffer, Sasha Zlobin, George Velez, Giorgio Apollinari, Vladimir Shiltsev, Sergey Belomestnykh, Anadi Canepa, Sergio Jindariani, Sam Posen

Global HEP Considerations

- There is broad consensus in the global HEP community that an e^+e^- Higgs Factory should be the next collider
 - Prime candidates: ILC, FCC-ee, CLIC, CEPC
 - Great physics potential, technology understood/feasible
 - Challenges: Funding, political and sociological, timescale
 - US to continue to strongly collaborate with international community on the ILC and FCC to help realize those machines.
- Snowmass is an opportunity for novel academic exercises and to focus international efforts
 - Alternate options for a Higgs Factory? Other Colliders?
 - Compact, modest cost, shorter timescale, physics potential
 - Part of global planning to advance Energy Frontier physics, technology
- Beyond the PIP-II/LBNF/DUNE project horizon
- Fermilab Future Colliders Group beginning to consider compact collider (Site Filler) options while also developing plans for engagement in ILC, and FCC efforts at CERN.
 - **International partnerships are critical for the health of our field.**

Compact (Site Filler) Collider Options

Circumference ≥ 16 km



Linear ~ 7 km



- Circular e+e- Higgs Factory (240 GeV)
 - Z, W, H
- Linear e+e- Higgs Factory (250 GeV)
 - Upgradeable to 360, 500 GeV ?
- Muon Collider – Higgs Factory to multi-TeV
 - 0.126 to 3,6,8,10 TeV
- pp Collider (24 – 28 TeV)
- (Other options: $\gamma\gamma$ collider, CLIC-K, ALC,..) \leftarrow won't cover

This talk is just a preliminary survey
 Lot more work needed for definitive answers!

Basic Assumptions/Specs

- Site, power constraints
- e+e- circular Higgs Factory
 - Peak lumi $> 1\text{e}34\text{ cm}^{-2}\text{ s}^{-1}$ (similar to LEP3, ILC)
 - $\sigma(\text{ZH}) \sim 200\text{ fb}$ @240 GeV
 - 20,000 Higgs events/ 10^7 s , with $1\text{e}34\text{ cm}^{-2}\text{ s}^{-1}$
 - $0.1\text{ ab}^{-1}/10^7\text{ s}$. → **0.2 ab^{-1} per year**
- $\mu+\mu-$ Higgs Factory (to multi-TeV)
 - Peak lumi $\sim 1\text{e}32\text{ cm}^{-2}\text{ s}^{-1}$ @126 GeV (MAP projection $\sim 0.8\text{e}32$)
 - 5x higher Lumi possible
 - $\sim 14,000 - 70,000\text{ Higgs}/10^7\text{ s}$
 - Higher luminosity at higher energies
- pp Collider
 - Energy 24-28 TeV (a proxy for HE-LHC)
 - Lumi well in excess of $1\text{e}34\text{ cm}^{-2}\text{ s}^{-1}$
- With any new machine, we need to consider sustainability, clean energy and environment!
(ICFA has a Panel on Sustainable Accelerators and Colliders!)



Circular e+e- Higgs Factory

Tanaji Sen

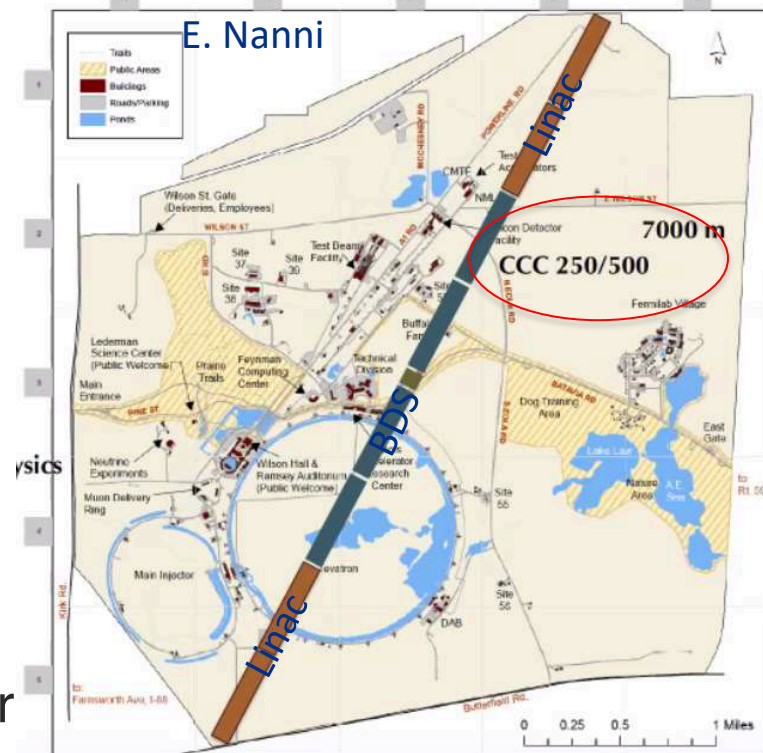
- Luminosity similar to LEP3 and slightly below ILC250
 - Can increase by allowing higher SR power => shorter beam lifetime
 - Novel ideas can help
- Beam Polarization?
 - Polarize beams before acceleration?
- Challenges:
 - IR optics with small β_y^* , control non-linear chromaticity, sufficient dynamic aperture, energy acceptance
 - Top-up injection needed due to low beam lifetime (successful at PEP and KEKB)
 - Synchrotron radiation effects
 - Vacuum system to deal with SR
 - RF systems: high efficiency, frequency choices, positioning along the ring
 - Vert. emittance: minimize growth

Circumference [km]	16.0
SR power, both beams [MW]	100
Energy [GeV]	120
Hourglass factor	0.81
β_x^*, β_y^* [cm]	20, 0.1
Particles/bunch	$8. \times 10^{11}$
Number of bunches	2
Beam-beam parameters ξ_x, ξ_y	0.075, 0.11
Beam current [mA]	5.0
Emittances [nm]	21, 0.05
Energy lost/turn [GeV]	10.0
Rf voltage [GV]	12.1
Damping time (τ_s) [turns]	12
Bremsstrahlung lifetime [mins]	8
Luminosity [cm ⁻² sec ⁻¹]	1.12×10^{34}

Linear Collider Higgs Factory

Cool Cooper Cavity (C³) LC

- SLAC proposal for a normal conducting linear accelerator/collider at 77K. (C3)
 - Could reach gradient ~ 120 MV/m
 - $1\text{--}2e34$ @250 GeV; using 70 -85 MV/m
 - Scalable to 500 GeV at FNAL \leftarrow more RF and higher gradient; to Multi-TeV if built off-site
- Benefits from R&D in other LC technologies
 - Beam Delivery system & IP (\sim ILC), Damping rings (CLIC)
- Single cavity tests yield excellent results
- C3 collaboration proposing a demonstrator facility
- Other LC options? Suggested:
 - CLIC-K (70 – 115 MV/m ?)
 - SRF-TW (~ 70 MV/m, proposed for ILC upgrade)
- Advancing design studies and R&D necessary



References for C3 option:

[Snowmass LoI](#),

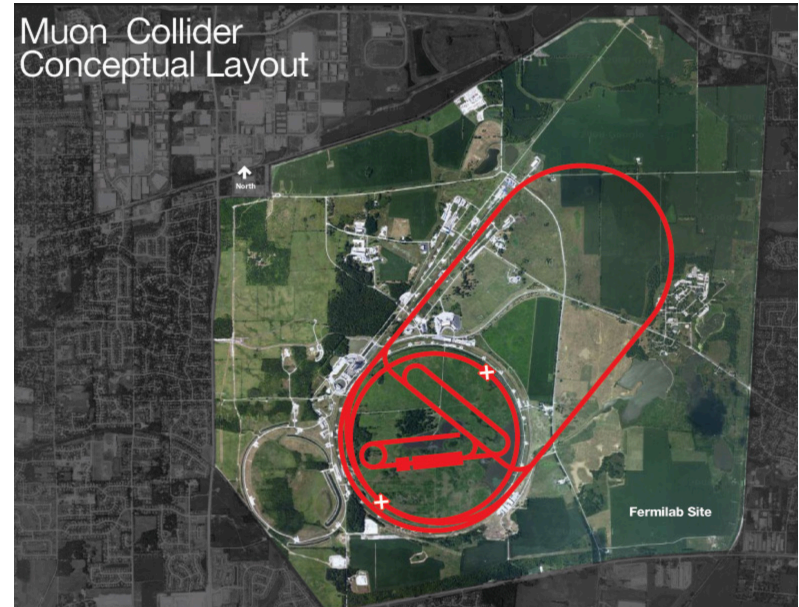
[Seminar at UW-Madison](#)

Bane et al., *arXiv* 1807.10195 (2018)

Talks at this Workshop

Muon Collider

- An explosion of interest recently in the collider community!
- A Compact collider for multi-TeV scale
- A precision and discovery machine
 - Excellent precision for Higgs coupling measurements
 - Great direct reach for new physics
 - $10 \text{ TeV } \mu^+\mu^- \cong 70 \text{ TeV } pp$
 - $10 \text{ TeV } \mu^+\mu^- \cong 150 \text{ TeV } pp \text{ for EW}$
- Technologically challenging, exciting, with unique opportunities for innovation
- Can be staged with physics at each stage:
 - Demonstrator facility, Higgs Factory, (nuSTORM), Multi-TeV Collider
- Intense ongoing work in the new International Muon Collider Collaboration and Snowmass Muon Collider Forum



125 GeV to 8 TeV (10 TeV?)
Muon collider can fit on site.
(14 TeV machine in the LHC tunnel)

} Machine scenarios, beam-induced background, neutrino radiation, detector/physics simulations

Muon Collider (contd.)

RAST, Vol 10, No. 01, pp. 189-214 (2019)

+ Neuffer

Muon Collider Parameters. $\sqrt{s} = 0.126 - 6 \text{ TeV}$						
Parameter	Units		Higgs 0.126 TeV	Top 0.35 TeV	3 TeV Collider	6 TeV Collider
Circumference	km		0.3	0.7	4.5	6
Ring Depth	m		135	135	135	540
Avg. Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$		0.008	0.6	4.4	12
# of IPs			1	1	2	2
$b_{x,y}^*$	cm		1.7	0.5	0.3 - 3	0.25
# of Muons/bunch	10^{12}		4	3	2	2
Trans. Emittance, e_T	p-mm-rad		0.2	0.05	0.025	0.025
Long emittance, e_L	p-mm-rad		1.5	10	70	70
Bunch Length	cm		6.3	0.5	0.5	0.2
Proton driver power	MW		4	4	4	1.6
Wall Plug Power	MW		200	203	230	270
# of Higgs/ 10^7 s			13,500	60,000	200,000	820,000
Max Mag. Field	T		8	8	10	16
RF	MV		6000	10000	15000	30000

Planned development of Fermilab accelerator complex for LBNF/DUNE will provide a robust infrastructure for a future muon collider

- Multi-MW proton beam with PIP-II linac and Booster replacement

Synergy with neutrino program via nuSTORM in the initial phase, and with precision physics program

A Compact Hadron Collider

- A Compact Hadron Collider at Fermilab
 - Site Filler (16 km ring, 24-28 TeV); need > 20 T LTS/HTS magnets
 - **Intermediate step to FCC and test bed for high field magnet use**
 - Efforts underway to look at preliminary designs, and technology R&D
- Planned development of the complex provide a robust injector infrastructure.
- The new machine can be an injector to a future VLHC (233 km pp collider.)
- Cheaper, high-field magnets critical.



Site-Filler pp Collider

FNAL-SF numbers T. Sen

parameter	FNAL SF	HE-LHC	FCC-hh	
collision energy cms [TeV]	24	27	100	
dipole field [T]	24.4	16	16	
circumference [km]	16	26.7	97.8	
beam current [A]	0.41	1.12	0.5	
bunch intensity [10^{11}]	1.05	2.2	1 (0.2)	1
bunch spacing [ns]	25	25	25 (5)	25
IP $b^*_{x,y}$ [m]	0.5, 0.5	0.45	1.1	0.3
luminosity/IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	15	5	30
peak #events/bunch crossing	135	800	170	1020
stored energy/beam [GJ]	0.26		8.4	
synchrotron rad. [W/m/beam]	3.9	3.74	30	
transv. emit. damping time [h]	1.8		1.1	
initial proton burn off time [h]	3.5	3.0	17.0	3.4

pp Collider Challenges

- High field dipole magnets
 - Requires fields above 20 T and also high field quality
- Interaction region magnets
 - Must withstand debris power from pp interactions
- Machine protection
 - Very high beam energy and magnetic energy, improved & sophisticated collimation required
- High synchrotron radiation
 - Impact on components, cryogenic system, radiation hard electronics
- Beam dynamics issues
 - Electron cloud effects, beam-beam interactions (head-on and long-range) & compensation, instabilities, crab cavity operation,
- Cost: ??

Key Challenge:

High Field Magnet Technology

- Current record for Nb₃Sn Magnet:
 - 16.5 T on conductor, 14.5 T magnet w/ 60 mm aperture
 - Attempts at 17-18 T ongoing
- Hybrid w/ HTS insert R&D
 - Results in the next couple of years
 - 20-25 T demo in the next 10 years
- US Magnet Development Program
 - Advance technology, improve performance, reduce cost
- IBS magnet research promising for >20T but early days
 - Need aggressive R&D
 - Might provide cheap and robust HF magnet option

Closing Remarks

- Snowmass provides the opportunity to consider and study facilities that can be hosted in the US, and to shape the US/global HEP program for the coming decades.
- The US community is already actively engaged in the efforts on the major global projects – the ILC effort in Japan and the FCC-ee/hh at CERN.
- Efforts to consider compact machines that might be realized on modest time scales and costs, could be profitable!

Compact (Site-Filler) Colliders

Circumference ≥ 16 km

Linear ~ 7 km



1. e+e- Site Filler Higgs Factory
2. Muon Collider Higgs Factory
3. Muon Collider 3-8 TeV
4. pp Site Filler Collider 24-28 TeV

Higgs Factories +

1. C3 (Cool Copper) linear collider
2. NC RF (CLIC-K) Collider
3. SRF-TW linear collider

Extra Slides

Key R&D Challenges

Issues

Status

Target

- Multi-MW Targets
- High Field, Large Bore Capture Solenoid

- Ongoing >1 MW target development
- Challenging engineering for capture solenoid

Front End

- Energy Deposition in FE Components
- RF in Magnetic Fields (see Cooling)

- Current designs handle energy deposition

Cooling

- RF in Magnetic Field
- High and Very High Field SC Magnets
- Overall Ionization Cooling Performance

- MAP designs use 20 MV/m → 50 MV/m demo
- >30 T solenoid demonstrated for Final Cooling
- Cooling design that achieves most goals

Acceleration

- Acceptance
- Ramping System
- Self-Consistent Design

- **Designs in place for accel to 125 GeV CoM**
- Magnet system development needed for TeV-scale
- Self-consistent design needed for TeV-scale

Collider Ring

- Magnet Strengths, Apertures, and Shielding
- High Energy Neutrino Radiation

- Self-consistent lattices with magnet conceptual design up to 3 TeV
- > ~5 TeV – ν radiation solution required

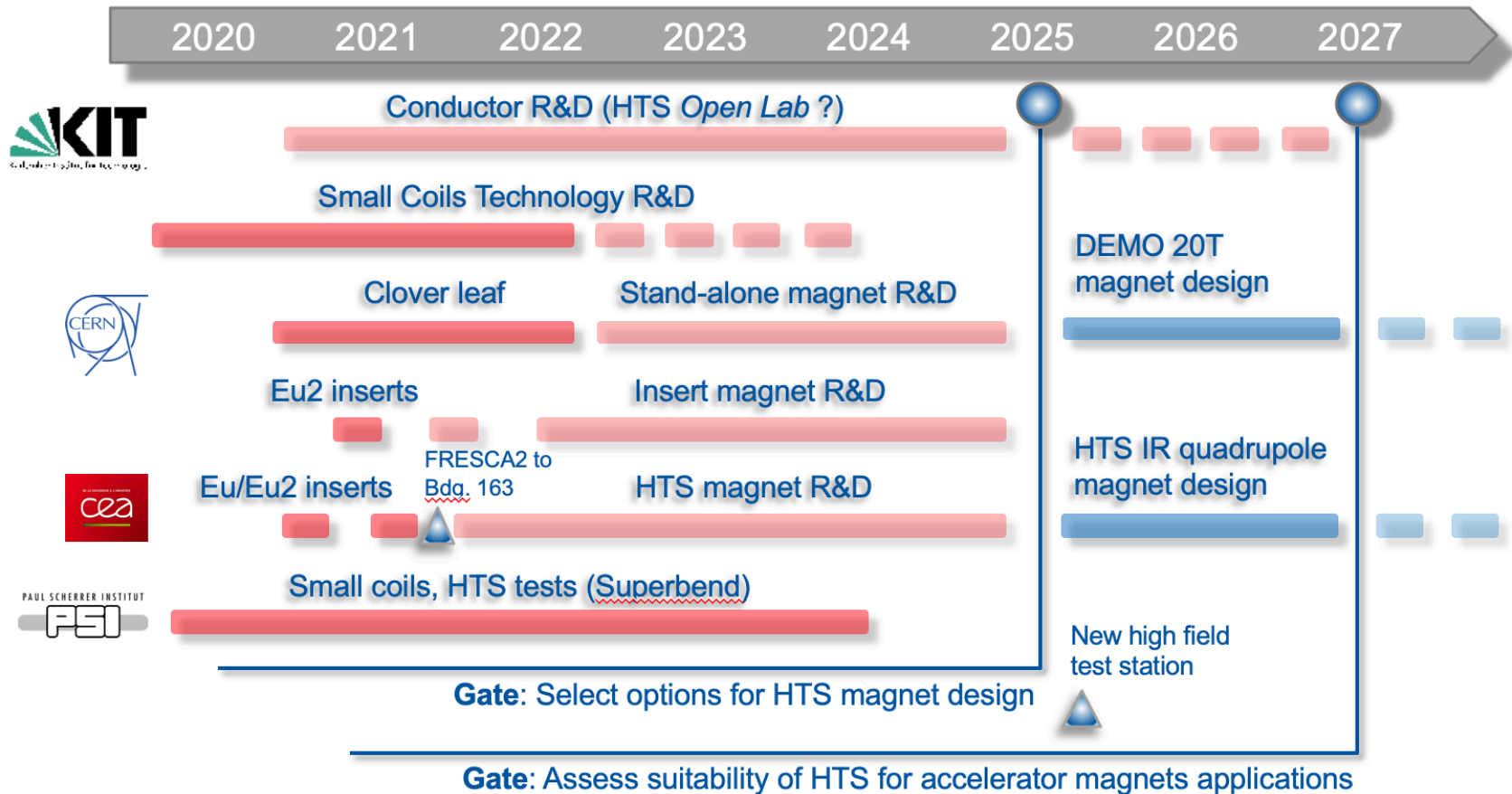
MDI/Detector

- Backgrounds from μ Decays
- IR Shielding

- **Further design work required for multi-TeV**
- Initial multi-TeV promising

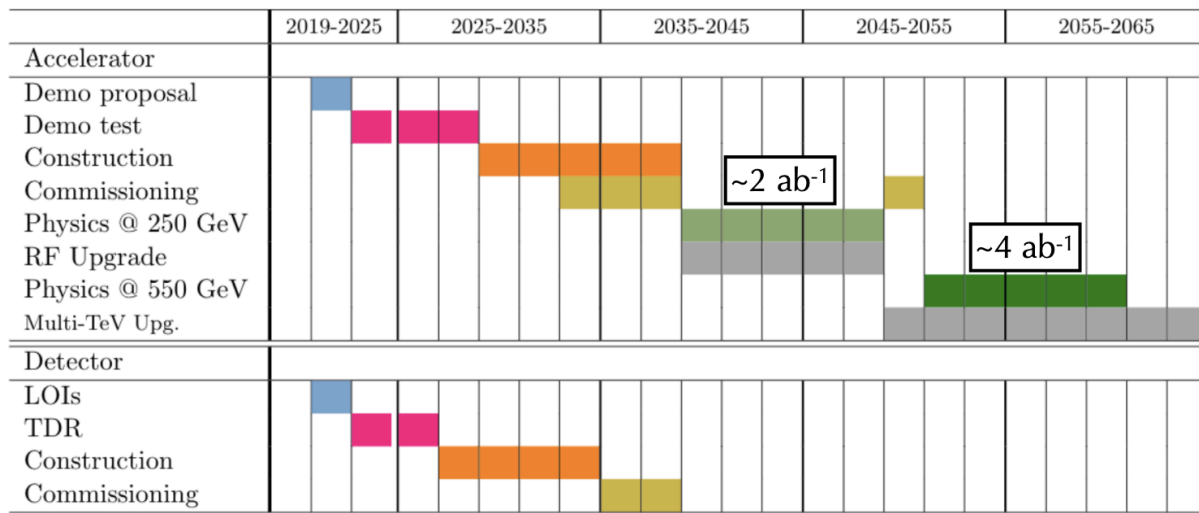
High Field Magnet R&D for pp Collider

CERN plan:



C³ timeline, parameters

C³ evolution: best timeline for the physics



HL-LHC

Collider	ILC	CCC
σ_z	300 μm	100 μm
β_x	8.0 mm	13 mm
β_y	0.41 mm	0.1 mm
ϵ_x	500 nm/rad	900 nm/rad
ϵ_y	35 nm/rad	20 nm/rad
N bunches	1312	133
Repetition rate	5 Hz	120 Hz
Crossing angle	0.014	0.020
Crab angle	0.014/2	0.020/2

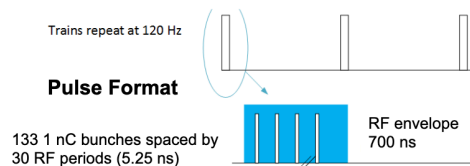
Summary of Parameters for 250 GeV Conceptual Design

SLAC

Luminosity - 1×10^{34}

Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load @ 77K (MW)	9
Electrical Load (MW)	100

Parameter (250 GeV CoM)	Units	Value
Reliquification Plant Cost	MS/MW	18
Single Beam Power (125 GeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Electrical Power for Cryo-Cooler	MW	60



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